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## Experimental Results on $B$ mesons from the $BABAR$ experiment

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Highlights of a selection of results obtained by the  $BABAR$  experiment on the PEP-II collider at SLAC until the spring of 2002 are presented. The phenomenology of CP violation in B decays is briefly reviewed. At that time, CP violation was already significantly established in the decays of neutral  $B$  mesons to charmonium and a neutral K:  $\sin 2\beta = 0.75 \pm 0.09 \pm 0.04$ . The analysis method and its implementation are described. The interpretation of the measurements and future prospects are discussed. Preliminary results on charmless and other rare  $B$  decays, that could lead to measurements of the CKM angles  $\alpha$  and  $\gamma$  are shown.

## 1 An overview of CP Violation in B decays

For CP violation to occur in  $B$  meson decay[1], at least two amplitudes, with a fundamental phase difference have to contribute. Three types of CP violation are distinguished[2, 3].

In *direct CP violation* the  $B$  and  $\bar{B}$  decay to CP conjugate final states with different rates. Direct CP violation requires both strong and weak phase differences. It can affect neutral and charged B mesons in contrast with the other types which rely on neutral  $B$  mixing.

*CP violation in mixing* occurs when  $\Delta B = 2$  transitions (box diagrams) exist which make mass eigenstates that are different from the CP eigenstates.

Finally *CP violation in the interference between mixing and decay* is the case where a final state built out of a CP self conjugate collection of quarks (which can be a CP eigenstate  $f_{CP}$ ) is reached either from a  $B^0$  or from a  $\bar{B}^0$  after a  $B^0 \rightarrow \bar{B}^0$  flavor oscillation.

A very clean theoretical situation is obtained in the last case when a single diagram dominates the  $B^0 \rightarrow f_{CP}$  transition (*golden mode*). A time dependent CP asymmetry (see Equation 1 below) follows from the opposite signs

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<sup>1</sup>representing the  $BABAR$  collaboration.



The rate of such a  $B^0$  decay has interference effects between that amplitude and that of  $B^0\bar{B}^0$  mixing which are free from strong interaction complications. When more than two decay paths with comparable strengths contribute, only an effective phase can be obtained.

More complicated processes can be used to search for CP violation at high luminosity. For example cascades[6] where  $T_{cus}$  and  $T_{ucs}$  transitions lead to a  $D$  or  $\bar{D}$  meson which decay to a final state they share in common have rates which depend on  $\gamma$ .

Table 1: CKM structure of non leptonic  $b$  decay amplitudes. The amplitude for a  $b \rightarrow q_1\bar{q}_2q_3$  transition is written in terms of T and/or P amplitudes with the CKM factors shown explicitly. The power of  $\lambda$  governing the first and second terms are given. A golden channel leads to a pure measurement of a CKM phase. Only *effective phases* are accessible from the non golden channels.

quark process	1st term	2nd		example	UT angle
$A_{ccs} \approx V_{cb}V_{cs}^*T_{ccs} + V_{ub}V_{us}^*P_s$	$\lambda^2$	$\lambda^4$	golden	$J/\psi K_{S,L}$	$\beta$
$A_{sss} \approx V_{cb}V_{cs}^*P_s + V_{ub}V_{us}^*P'_s$	$\lambda^2$	$\lambda^4$	golden	$\Phi K_S^0$	$\beta$
$A_{ccd} \approx V_{cb}V_{cd}^*T_{ccd} + V_{tb}V_{td}^*P_d$	$\lambda^3$	$\lambda^3$		$D^+D^-$	$\beta + \theta$
$A_{uud} \approx V_{ub}V_{ud}^*T_{uud} + V_{tb}V_{td}^*P_d$	$\lambda^3$	$\lambda^3$		$\pi^+\pi^-$	$\alpha_{eff}$

## 2 Experimental setup and analysis tools

### 2.1 PEP-II and BABAR

CP violation in the interference between mixing and decay produce time dependent CP-asymmetries. For a CP eigenstate  $f_{CP}$ :

$$\begin{aligned}
A_{f_{CP}} &= \frac{\Gamma(\bar{B}_{phys}^0(t) \rightarrow f_{CP}) - \Gamma(B_{phys}^0(t) \rightarrow f_{CP})}{\Gamma(\bar{B}_{phys}^0(t) \rightarrow f_{CP}) + \Gamma(B_{phys}^0(t) \rightarrow f_{CP})} \\
&= C_{f_{CP}} \cos(\Delta m_d t) + S_{f_{CP}} \sin(\Delta m_d t).
\end{aligned} \tag{1}$$

In Eq. (1),  $t$  is the proper time elapsed between the production of a  $B$  meson with known flavor (beauty) and its decay.  $B_{phys}(t)$  is the evolved  $B$  state

after  $t$ . Neglecting  $\mathcal{O}(t^2)$  terms, the coefficients can be written:

$$C_{f_{CP}} = \frac{1}{1 + |\lambda_{f_{CP}}|^2}, \quad S_{f_{CP}} = \frac{-2\text{Im}(\lambda_{f_{CP}})}{1 + |\lambda_{f_{CP}}|^2}. \quad (2)$$

where  $\lambda_{f_{CP}} = \frac{q}{p} \times \frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}} \times \eta_{CP}$ ,  $q$  and  $p$  are the mixing parameters,  $A$  ( $\overline{A}$ ) are the  $B^0$  (resp.  $\overline{B}^0$ )  $\rightarrow f_{CP}$  amplitudes and  $\eta_{CP}$  is the CP parity of the  $f_{CP}$  state. A non-zero  $C_{f_{CP}}$  is evidence for *direct CP violation*. For the  $B^0 \rightarrow \pi^0 \pi^0$  mode  $|A| = |\overline{A}|$ , and  $|S_{f_{CP}}|$  is the sine of a CKM angle. For the  $B^0 \rightarrow \pi^0 \pi^0$  mode in Table 1,  $S_{f_{CP}} = \eta_{CP} \times \sin 2\beta$ .

To be capable of measuring CP asymmetries, the experiment must fulfill the following requirements:

- Since the  $f_{CP}$  branching ratio is small (e.g.  $B^0 \rightarrow \pi^0 \pi^0$  is  $\sim 10^{-8}$ ), a high luminosity is required to detect a significant number of events. PEP-II at SLAC and KEKB at KEK are the only colliders which decay exclusively to  $B$  mesons with a production rate above a manageable background.

**High performance vertex detectors** are required to reconstruct pure samples of  $B$  mesons.

To tag the initial  $B$  meson, **particle identification** is needed.

To measure the time difference, the particles have to fly far enough in the laboratory. This is achieved by using  $4S$ , using **different electron and positron energies**.

In an asymmetric  $B$  Factory, one needs a large boost to make the decay point is displaced from the production point.

With 9 GeV  $e^+e^-$  colliders, the average mean lifetime of the  $B$  meson is

laboratory. The distance traveled by the  $B$  meson is

$10^{33} \text{ cm}$

The results presented here are based on an integrated luminosity of  $56.4 \text{ fb}^{-1}$ , of which 6.5 were taken at an energy below that of the  $\Upsilon(4S)$  resonance.

## 2.2 Experimental technique

Time dependent CP-asymmetries are studied in samples of  $B^0\bar{B}^0$  events where one  $B$  meson decays to a completely reconstructible exclusive non leptonic final state and the other, to a flavor specific mode. Before any decay, the  $B\bar{B}$  pair is in a coherent  $L=1$  quantum state i.e. it remains a particle-antiparticle pair. When the flavor specific decay occurs, the other  $B$  has the opposite flavor. It then evolves in the way prescribed by  $B\bar{B}$  mixing. This argument holds whatever the time ordering of the two decays[2, 3]. To analyse CP-asymmetries, the experimental technique[8] consists in implementing the exclusive  $B$  meson reconstruction, the  $B$  flavor tagging and the vertexing algorithm for the determination of  $\Delta t$ .

Very pure samples (see section 3) are selected for  $f_{CP}$  as well as flavor eigenstates using two kinematic variables  $\Delta E$  and  $m_{ES}$ .  $\Delta E$  is the difference in the center of mass frame between the energy of the  $B$  candidate and the beam energy.  $m_{ES}$  is the invariant mass of the  $B$  candidate computed from the candidate momentum and the beam energy which is much more precisely known than the candidate energy.

To determine  $\Delta t$ , the projection  $\Delta z$  along the electron beam of the vector joining the decay points of the two  $B$  mesons is measured. The vertex of the fully reconstructed  $B$  is obtained from a geometric and kinematic fit of the candidate. The other  $B$  decay point is obtained iteratively from the charged tracks which remain after removal of those belonging to the reconstructed candidates and those with which a  $V^0$  ( $K_s^0$  or  $\Lambda$ ) can be constructed. That vertex is constrained to be compatible with the flight path of that  $B$  (new)  $B$  (old) (tagged)  $B$  (new)  $B$  (old) (tagged)

2971 0 Td (v)Tj 5.7491 0 Td Td (j 4(w)Tj 8.0325 11.9

the  $\Delta t$  resolution is needed with parameters to be fitted from the data. A hierarchical B flavor tagging algorithm using four non overlapping sets of criteria (categories) exploits the charge correlations between the b quark and the leptons or kaons produced in the CKM-favored  $b \rightarrow c(\rightarrow s)$  quark decay chain. More global information (e.g. charged particle momentum spectrum, soft pions from  $D^*$  decays, etc.) are input to neural networks used to complete the tagging algorithm. The efficiency  $\varepsilon \approx 0.7$  and the mistag fraction  $w$  characterize the performance. The overall effective efficiency is  $Q = \varepsilon \times (1 - 2w)^2 = 0.251 \pm 0.008$ .

To validate the experimental techniques, the lifetimes of the  $B$  mesons and the  $B^0\bar{B}^0$  oscillation frequencies are measured using appropriate reconstructed samples. The  $\Delta t$  distributions obtained for charged and neutral  $B$  s are shown on Fig. 3. The measured lifetimes:  $\tau_0 = 1.546 \pm 0.032(stat.) \pm 0.022(syst.)$  ps,  $\tau_{\pm} = 1.673 \pm 0.032 \pm 0.023$  ps, are compatible with previous measurements[10] and have smaller errors. The lifetime ratio measurement[9],  $\tau_{\pm}/\tau_0 = 1.082 \pm 0.026 \pm 0.012$  promises an ultimate error at the level of 1 %. Similarly, samples of reconstructed neutral  $B$  mesons decaying to flavored final states enabled to extract the averaged mistag fraction and also showed compatibility of the measured  $B^0\bar{B}^0$  oscillation frequency  $\Delta m_d$  with previous measurements.

### 3 The measurement of $\sin 2\beta$ .

Table 2: Yields in the  $B$  reconstruction  $f_{CP}$  modes after tagging. Note that for the  $J/\psi K^{*0}$  final state a partial wave analysis is needed to separate the CP-even and CP-odd contributions.

Mode	$N_{tagged}$	Purity
$(c\bar{c})K_s^0$	995	94%
$J/\psi K_L^0$	742	57%
$J/\psi K^{*0}$	113	83%
All CP	1850	79%

Some of the yields measured for the golden modes  $B^0 \rightarrow \text{charmonium } K_s^0$  as well as  $\rightarrow \text{charmonium } K_L^0$  (more difficult to select because the  $K_L^0$  energy is not measured) are shown on Fig. 4 and summarized in Table 2. Since the tagging performance is the same for both samples, the  $\Delta t$  distributions for tagged flavored  $B$  and  $f_{CP}$  samples are simultaneously fit keeping  $\tau_0$  and  $\Delta m_d$  fixed at the previous pre- $BABAR$  values[10]. The result for a sine-wave only  $A_{CP}(\Delta t)$  is:  $\sin 2\beta = 0.75 \pm 0.09 \pm 0.04$ .

The CP asymmetries as a function of  $\Delta t$  are shown on Fig. 5 for CP-odd and CP-even channels with the likelihood projections superimposed. Out of phase sine waves are observed as expected. Since the conference, that measurement has been updated[11] to  $\sin 2\beta = 0.741 \pm 0.067 \pm 0.033$ . A similar result[12]  $0.719 \pm 0.074 \pm 0.035$  is obtained by the BELLE experiment. Consistent results are obtained in *BABAR* by doing fits looking at one decay channel only.

Control samples (e.g. flavored *B* s) with null expectations indeed give results compatible with zero. A fit allowing both sine and cosine waves in the  $A_{CP}$  time dependence gives  $\lambda_{f_{CP}} = 0.92 \pm 0.06 \pm 0.02$ . That value being compatible with 1, there is no evidence for direct CP violation.

Fig. 4 Charmonium  $K_S^0$  and  $J/\psi K_L^0$  yields.

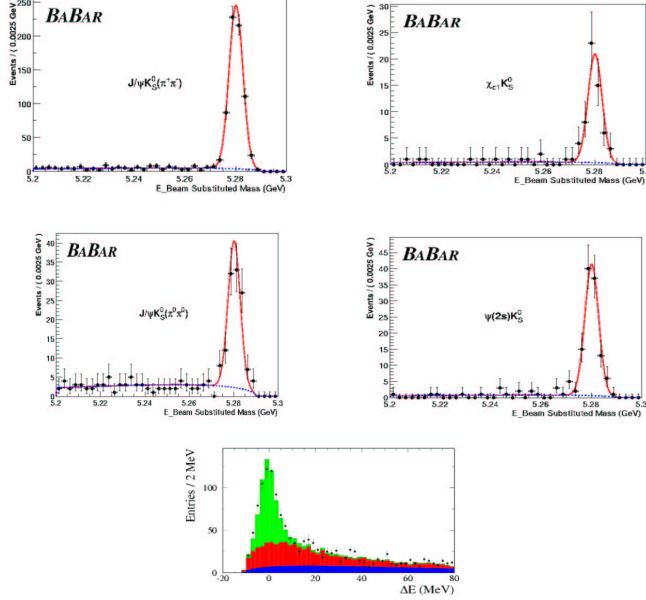
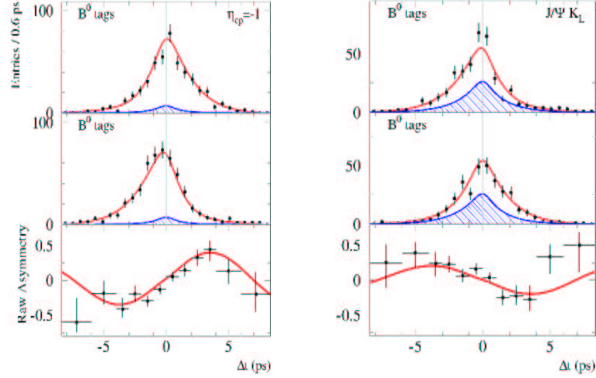


Fig. 5  $A_{CP}(\Delta t)$  for CP= $\mp$ 1.



The 1 and 2-standard deviation zones for  $\sin 2\beta$  in the  $(\rho, \eta)$  plot are shown on Fig. 6. There is a four-fold trigonometric ambiguity. One solution agrees with previous non-CP measurements. The standard model is resilient. A preliminary result on  $B^0 \rightarrow \eta_c K_S^0$  (first line of Table 1) was shown at the conference:  $\sin 2\beta = 0.43 \pm 0.46 \pm 0.08$ . Although signals were seen in  $B \rightarrow \Phi K$  channels, no result was available for the pure penguin  $A_{CP}$ .



The  $S_{DD}$  and  $C_{DD}$  coefficients of Eq.( 1), for  $B \rightarrow D^{(*)+}D^{(*)-}$  decays are summarized in Table 3. More data are needed before any conclusions can be drawn from these measurements.

In summary, CP violation has been discovered by the experiments at the  $B$  factories. At the current level of precision, all the data are compatible with the standard (CKM) model.

Fig. 6 1 and 2  $\sigma_{\sin 2\beta}$  bands on UT plot.

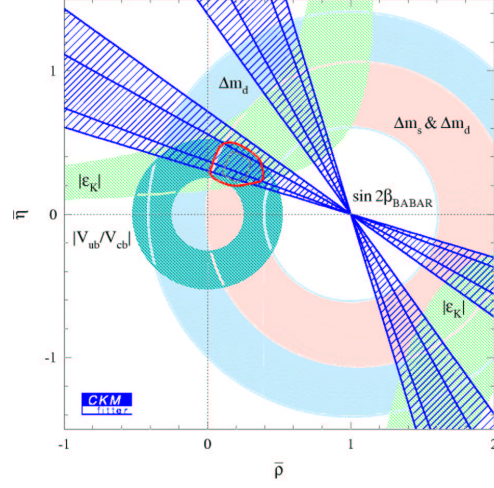


Table 3: Preliminary results on the  $B^0 \rightarrow D^{(*)+}D^{(*)-}$  coefficients  $S_{DD}$  and  $C_{DD}$ .

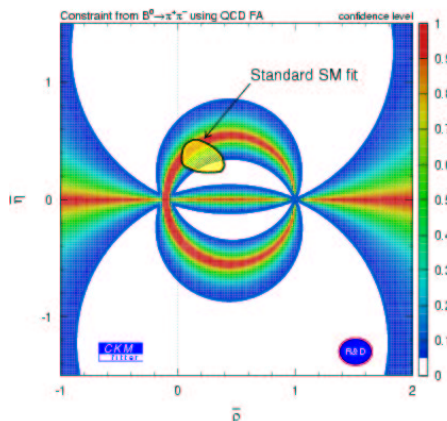
Mode	$S_{DD}$	$C_{DD}$
$D^{*+}D^{*-}$	$-0.05 \pm 0.45 \pm 0.07$	$0.12 \pm 0.30 \pm 0.03$
$D^{*+}D^-$	$-0.43 \pm 1.41 \pm 0.20$	$0.53 \pm 0.74 \pm 0.13$
$D^{*-}D^+$	$0.38 \pm 0.88 \pm 0.05$	$0.30 \pm 0.50 \pm 0.08$

## 4 Towards $\sin 2\alpha_{eff}$

$B$  decays to two-body final states without charmed hadrons (*charmless 2-body channels*) could give access to the  $\alpha$  and  $\gamma$  angles of the UT. Originally, the  $B^0 \rightarrow \pi^+\pi^-$  channel looked like a golden mode for  $\sin 2\alpha$ . But it was soon realized that penguin graphs  $P_d$  competed with the  $T_{uud}$  at  $O(\lambda^3)$  (see the last line of Table 1). Unless  $|P/T| \ll 1$ , three amplitudes interfere,  $P$ ,  $T$ , and that of mixing. A fit to  $A_{CP}^{\pi^+\pi^-}$ , pretending that it is a golden channel, can at best determine (the sine of) an effective phase  $\alpha_{eff}$ . The present analyses fit for the  $C_{\pi\pi}$  and  $S_{\pi\pi}$  coefficients defined in Eq. (2). With more theoretical input like isospin invariance, SU(3) symmetry or relying on QCD inspired models[13, 14] to compute the  $P$  and  $T$  amplitudes, conclusions on CKM angles can be reached. They are however subject to theoretical errors. It is much harder to implement the experimental technique for charmless

decays because the branching ratios of these CKM or penguin suppressed decays are tiny (in the  $10^{-5}$  or  $10^{-6}$  range) and because the final states have much weaker kinematical or topological constraints. Particle identification at high momenta where the DIRC is effective and methods to efficiently remove the continuum  $e^+e^- \rightarrow q\bar{q}$  are employed on top of tagging and vertexing. The final states including charged pions and kaons are treated simultaneously. On top of  $m_{ES}$  and  $\Delta E$ , other discriminating variables are used, namely a Fischer discriminant which characterizes the event energy flow and the DIRC Cherenkov angles of the charged particles. The analyses are performed in two steps. In the first, the CP-averaged branching ratios and the time integrated CP asymmetries are determined. The results of the first step are injected as fixed quantities in the time dependent analyses (second step) which apply tagging and vertexing. All results are preliminary. They are constantly re-fined. The time integrated results are summarized in Table 4. The experiment is becoming sensitive to the final states with  $\pi^0$  s which are needed in isospin constructions. In May 2002, the fit to  $A_{CP}^{\pi^+\pi^-}(\Delta t)$  gave:  $C_{\pi\pi} = -0.01 \pm 0.37 \pm 0.07$ ,  $S_{\pi\pi} = -0.02 \pm 0.29 \pm 0.07$ . The numbers have since moved within errors. For fun, the  $(\rho, \eta)$  plot assuming the validity of a model[13] is pictured on Fig. 7. Any conclusions about the CKM angles are premature.

Fig. 7  $(\rho, \eta)$  for  $B^0 \rightarrow \pi\pi$  with model[13].



## 5 Rare decays

At the conference, preliminary results were mentioned very briefly on rare decays, like the  $B^\pm \rightarrow DK^\pm$  where the  $D$  decays to  $K^+K^-$ , a CP eigenstate shared by the  $D$  and the  $\bar{D}$  (see the very end of section 1). Results on a host of (two-body and quasi two-body) charmless modes were listed. The high branching ratios of  $\eta' K$  channels is confirmed. No significant direct CP asymmetries have been found in charged  $B$  decays. The status of electroweak

Table 4: Preliminary results on  $B \rightarrow$  charmless 2-body decays as of May 2002. CP averaged branching ratios and time integrated CP asymmetries (direct CP violation) are presented. Most of these results have been updated since then. The  $B^+ \rightarrow K^0 \pi^+$  asymmetry, all the  $B^+ \rightarrow \pi^+ \pi^0$  and  $B^0 \rightarrow \pi^0 \pi^0$  results were recent. The  $K^0 \pi^0$  and  $K^0 \bar{K}^0$  are based on  $20.6 \text{ fb}^{-1}$  of data only.

$B \rightarrow$	Yield	Signif.	BR ( $10^{-6}$ )	$A_{direct}$
$K^+ \pi^-$	$403 \pm 24$		$17.8 \pm 1.1 \pm 0.8$	
$K^+ \pi^0$	$149 \pm 17^{+8}_{-7}$		$11.1^{+1.3}_{-1.2} \pm 1.0$	
$K^0 \pi^+$	$172 \pm 17 \pm 9$	17.8	$17.5^{+1.8}_{-1.7} \pm 1.8$	$-0.17 \pm 0.10 \pm 0.02$
$K^0 \pi^0$	$17.9^{+6.8}_{-5.8} \pm 1.9$	4.5	$8.2^{+3.2}_{-2.7} \pm 1.2$	$0.00 \pm 0.11 \pm 0.02$
$\pi^+ \pi^-$	$125^{+16}_{-15}$		$5.4 \pm 0.7 \pm 0.5$	
$\pi^+ \pi^0$	$62^{+17}_{-16} \pm 10$	5.2	$4.1^{+1.1}_{-1.0} \pm 0.8$	$-0.02^{+0.27}_{-0.26} \pm 0.10$
$\pi^0 \pi^0$	$9.8 \pm 8.7$	1.3	$< 3.4$	
$K^+ K^-$	$0.6^{+8.0}_{-7.4}$		$< 1.1$	
$K^+ \bar{K}^0$	$-5.6^{+2.8}_{-5.5} \pm 2.5$		$< 3.8$	
$K^0 \bar{K}^0$	$3.5^{+3.4}_{-2.4}$	1.5	$< 13$	

penguin decays branching ratios was given:

$$Br(B \rightarrow K \ell^+ \ell^-) = 0.84^{+0.30}_{-0.24} \pm 0.10^{+0.10}_{-0.18} \times 10^{-6} \quad Br(B \rightarrow K^* \ell^+ \ell^-) < 3.5 \times 10^{-6} \text{ at } 90 \% \text{ c.l.}$$

## 6 Summary and outlook

The *BABAR* measurement of  $\sin 2\beta$  had reached a precision of 0.09 at the time of the conference and of 0.067 since then[11]. There is still headroom before it becomes dominated by the systematic errors (at the level of 0.03).

Charmless  $B$  decays are the focus of many analyses. There is steady progress towards significant measurements of  $\sin 2\alpha_{eff}$  in two and now three pion final states.

Many modes testing the same standard model parameters via different graphs will be constantly scrutinized, looking for new physics.

The abundant harvest of experimental data on many branching ratios and asymmetries will help to refine the theoretical knowledge of  $B$  decays.

Scenarios to accelerate progress towards higher luminosities and reach  $\text{ab}^{-1}$  samples sooner than presently planned are actively studied.

## Acknowledgments

I am grateful for the superb achievements of the PEP-II staff. I am delighted to present so many excellent pieces of physics worked out by my *BABAR* colleagues. I wish to warmly thank the organizers of the conference who prepared a full, diverse and exciting program and very smoothly managed the event. I will remember many participants for their talks and for the friendly discussions we enjoyed together.

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